Driving energy and resource efficiency through chemical engineering

Controlled Phase Cycle, viably transforming low grade waste heat into electricity

Low grade waste heat, which would often otherwise be wasted, is becoming a viable source of carbon-efficient electricity.

Introduction

This case study describes the development and application of a new heat-to-power cycle that can viably recover energy from low-temperature waste heat streams.

Most of the waste heat from industrial processes (more than 60% = 10–20 PWh globally) is rejected to the environment as low grade heat below 100°C. This makes its direct use within a facility difficult and reduces the potential for power generation using traditional Rankine or Organic Rankine Cycles (ORCs). ORCs require that adequate pressure and temperature differential is maintained in a principally isothermal process. It is the isothermal nature of ORC that limits the temperature that the heat source can be cooled to and therefore heat recovery and power generation potential. In practice, with a maximum waste stream temperature of 85°C, an ORC system will operate most effectively at a refrigerant boiling temperature of 55°C. Allowing for heat exchanger approach temperatures, this means the waste stream will exit at a minimum temperature of 60°C. The energy available from cooling the waste stream from 60°C to close to ambient temperature is effectively wasted.

Reduction of emissions: Generating electricity from low-temperature waste heat replaces fossil fuels, leading to substantial reduction of greenhouse gases and the CO_2 footprint of the facility.

Security of supply: The generation of electricity from a waste heat source reduces the amount of primary fuel required and provides an alternative source of energy.

Cost savings: Using waste heat will result in significant cost savings for the users. The system is optimised for maximum efficiency at heat source temperatures 75°C to 90°C to maximise the range of applications and potential markets. The system is very cost efficient, and the payback period is projected to be 1.3–5 years depending on the installation specifications.

This study covers a period of four years of intensive research and development on modelling various cycles, explored and validated through careful testing and supported by novel techno-economic and life cycle analysis approaches.

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Developing the Cycle

The Controlled Phase Cycle (CPC) was developed from the Trilateral Flash Cycle (TFC) (Figure 1). Commercial viability of the CPC has previously been hindered by the low efficiency of available expanders and high parasitic losses, particularly pumping power.

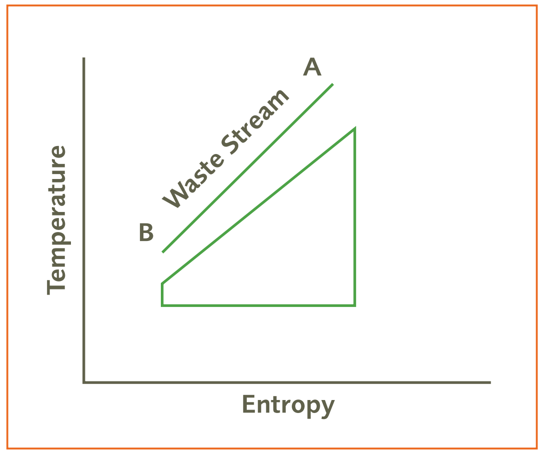

Figure 1. T-s plot for Trilateral Flash Cycle

The TFC is a three-leg power cycle in which the working fluid expands from saturated liquid state at high pressure to a two-phase state at lower pressure in an expander, before rejecting heat and returning to liquid phase in the condenser.

The resulting liquid is then compressed by a pump to the higher-pressure level before it is heated up by the heat source (waste heat stream) and re-expanded. Such a cycle allows the predominantly isothermal heat exchange associated with ORC to be replaced by a counter-current heat exchanger. This transfers almost all of the available heat to the cycle, significantly increasing the power output compared to the conventional ORC and allowing the production system to be fully heat integrated with the cycle.

Thermodynamic modelling of a CPC with a twin-screw expander revealed that dynamically adjusting the phase of the heated liquid on exit from the counter-current heater could provide extra conversion efficiency and optimisation of the working fluid mass flow rate. This was achieved by matching the working fluid inlet and outlet conditions to the expansion performance of the expander. Such expansion performance is linked to the built-in volume ratio and the effects of differing mass flow rates as conditions change with waste stream and cold sink temperatures. Dynamic control was therefore required, and this was achieved with a control valve sized and adjusted to isenthalpically modify phase and pressure at the expander inlet. Positioning of the valve is based on the output of a full thermodynamic model of the cycle built into the CPC control system.

The CPC cycle is shown on the temperature entropy diagram for R1233 zd refrigerant below (Figure 2).

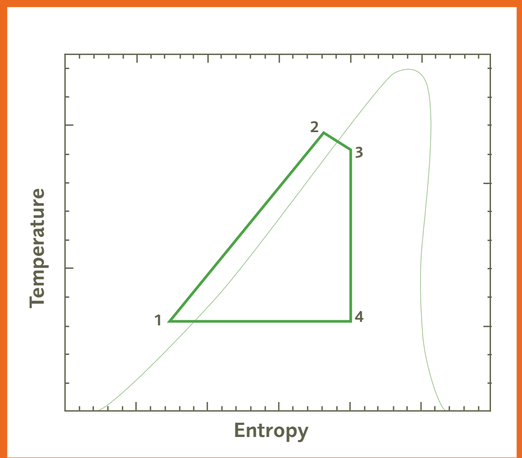

Figure 2. T-s diagram for Controlled Phase Cycle with R1233zd(E)

Point 1 to 2:- Pump liquid to pressure and heat to just below saturation point (2.15 bar)

Point 2 to 3:- Isenthalpic expansion to match real ratio volume of expander and system (variable pressure drop typically 1–2 bar)

Point 3 to 4:- Expansion in screw expander creating shaft power (typically 12.19–2.15 bar)

Point 4 to 1:- Condense gas in output mixture to return to point 1

Further modelling of various environmentally friendly refrigerants and expander sizes led to a range of solutions where the parasitic pumping power was greatly reduced. The net impact was a commercially compelling solution that can generate customer paybacks in the order of 1.5 to 2.5 years depending on electricity value and hours of operation. The performance of the CPC was confirmed on a 500 kW test rig at Spirax Sarco Test Facility in Cheltenham, UK.

Industrial Demonstration of the CPC

In order to demonstrate the new technology at industrial scale a consortium was formed of Spirax Sarco, Brunel University London, Howden Compressors, IPU Ltd (SME), Arctic Circle (SME), and Cooper Tires (user of the technology) and Innovate UK funding. The group sought, successfully, to demonstrate the CPC technology on a waste stream at Cooper Tires.

This funding significantly reduced the risk of the rapid scale-up to an industrial solution. The funding also provided the academic resource and skills in cycle modelling to improve the design and control of the system.

Many industries mix their waste streams together before pumping to a cooling tower. This results in a waste stream of lower temperatures (below 65°C). Cooper Tires' process was ideal for the demonstration project, as the waste stream is undiluted.

Cooper Tire uses high pressure hot water to mould and vulcanise tyres, which is then rejected at the end of each cycle. The wastewater is sent back to the boiler house. There, some of the waste stream is used to pre-heat boiler water, but approximately 2 MW of heat is excess and available for energy conversion. The temperature of this waste water is variable depending on the season and ambient temperature but is in the range of 75–95°C.

The factory site at Melksham was also ideal, as a suitable cold sink is available in the form of incoming river water extracted under license. The test system was designed to raise this stream's temperature by only 2–3°C.

Detailed design of the system was aided by 1D validated models of the screw expander and heat exchangers by Brunel University London.

The unit was built, tested and delivered to site in January 2018, after a commissioning period, the new cycle was demonstrated, and the unit has been running successfully since March 2018.

Impacts

The unit will deliver 720 MWh net of electricity to the factory per annum once fully operational, reducing the load to the national electricity grid. This has a savings value to Cooper Tire of approx. £70,000 per annum and reduces the carbon footprint of the factory by 510 tonnes/year of CO_2. The unit qualifies for enhanced capital allowance and will achieve a simple payback of 2.5 years with an internal rate of return of over 30%, including all maintenance and service costs.

Uptake of CPC's to the manufacturing sector would bring about substantial savings in CO_2 and electricity, whilst providing a compelling business case in terms of economic, energy and resource efficiency. It opens the door to a new vision of "cooling towers expelling waste heat" to a "cooling tower that produces electricity".

This case study was produced by the Institution of Chemical Engineers Energy Centre in partnership with Spirax Sarco Ltd and Brunel University. For more information on the work of the Energy Centre, visit **http://www.icheme.org/energycentre** or contact **energycentre@icheme.org**

Lessons for chemical engineers

Thermal waste streams can provide an opportunity to de-carbonise and save money. Evaluating your waste streams and isolating and recovering from the ones with higher energy, ie with temperatures above 65°C, can provide a valuable source of savings.

Thermal modelling calibrated by detailed and scaled testing can provide real solutions for profitable manufacture in a lower carbon world.

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Contact us for further information

UK
t: +44 (0)1788 578214
e: membersupport@icheme.org

Australia
t: +61 (0)3 9642 4494
e: austmembers@icheme.org

Malaysia
t: +603 2283 1381
e: malaysianmembers@icheme.org

New Zealand
t: +64 (4)473 4398
e: nzmembers@icheme.org

Singapore
t: +65 6250 0385
e: singaporemembers@icheme.org

www.icheme.org

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